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RESEARCH MEMORANDUM

PRELIMINARY STUDIES OF ROLLING-CONTACT FATIGUE LIFE OF HIGH-TEMPERATURE BEARING MATERIALS

By Thomas L. Carter

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS
WASHINGTON
April 1, 1958

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SUMMARY

A preliminary investigation of the rolling-contact fatigue life of some promising high-temperature bearing materials was made in the rolling-contact fatigue spin rig.

Groups of about 30 balls were run at a maximum theoretical Hertz compressive stress of 725,000 pounds per square inch with a paraffinic-base mineral oil lubricant at room temperature. The following ball materials were investigated: SAE 52100, MHT, TMT, MV-1, Halmo, and AISI T-1, M-1, M-10, and M-50. Groups of AISI M-1 air-melt and vacuum-melt balls were run with a water-base glycol under the same test conditions. Groups of AISI M-1, MV-1, M-1 vacuum-melt, and T-1 races were run at room temperature with a paraffinic mineral oil at a maximum theoretical Hertz compressive stress of 750,000 pounds per square inch. The following observations were made:

(1) Vacuum-melting improved fatigue life for AISI M-1 tool steel. This was true for both balls and races.

(2) Further aluminum and silicon additions, with or without molybdenum modifications, to the basic SAE 52100 composition improved fatigue-life performance with no apparent change in cleanliness.

(3) No correlation of rolling-contact fatigue life with cleanliness was obtained. This factor may have been overshadowed by variations in composition.

INTRODUCTION

A critical need exists for rolling-contact bearings which will give sustained performance at temperatures to 750° F (refs. 1 and 2). This need has created a demand for ball and race materials which have adequate

hot hardness and dimensional stability. At the same time these materials must possess adequate fatigue life at temperatures to 750° F. While a number of existing alloys are known to possess adequate hot hardness and dimensional stability, rolling-contact fatigue data are needed to determine which materials warrant further investigation and improvement.

It would be ideal to obtain fatigue data at the actual operating temperatures, but lubricants with satisfactory thermal stability at these temperatures do not exist. Therefore, tests at room temperature have been conducted as initial screening tests in the hope that the fatigue life at room temperature may be of value in indicating what may be expected at elevated temperatures.

Two basic problems must be recognized in compiling and analyzing rolling-contact fatigue data. The first involves the statistical reliability of data obtained by testing a relatively small number of specimens which represent only a minute portion of the heat being evaluated. The second problem concerns the nonhomogeneity of an alloy from heat to heat, and probably within each heat, depending on position within the ingot. Therefore, a determination of fatigue life for one heat of materials, no matter how accurate it may be, can by no means be considered representative of the alloy in general. Fatigue life data must be produced for a number of heats from a number of different sources before any general conclusions can be made regarding the rolling-contact fatigue life of a given alloy.

The objects of this investigation are: (1) to obtain room-temperature fatigue life data for standard bearing alloys and promising high-temperature alloys for comparative purposes and to indicate which of the high-temperature alloys have the most promise for high-temperature tests, and (2) to permit later comparison of room-temperature and high-temperature fatigue tests.

The results published herein are considered preliminary in nature and should not, for the reasons stated above, be taken as the base for general conclusions.

APPARATUS

Only brief descriptions of the apparatus and procedure are given here. A detailed presentation can be found in reference 3. Figure 1(a) is a cutaway view of the rolling-contact fatigue spin rig. Two balls driven by an air jet revolved in a horizontal plane on the bore surface of a hardened tool-steel cylinder (fig. 1(b)). The loading on the balls was produced by centrifugal force, and the stress was calculated according to the methods of reference 4. Approximately 15 milliliters per hour of lubricant were introduced into the drive airstream in droplet form between the guide plates. The fast-moving airstream had an atomizer effect, and the lubricant was reduced to a fine mist which adhered to surfaces to provide a lubricating film.

Orbital speed was measured by counting the pulses from a photoamplifier on an electronic tachometer. A pulse is generated each time a ball interrupts a light beam. A ball or race failure resulted in increased amplitude of vibration and, hence, in an increased signal from a vibration pickup attached to the rig. This signal actuated a meter relay which shut down the system.

Ball specimens were in groups of 13 to 74 for the alloys investigated. They were all 1/2 inch in diameter with the exception of the SAE 52100 specimens which were 9/16 inch in diameter. The running track on the balls was predetermined by grinding two diametrically opposed 1/8-inch flats on the ball surface. This procedure simplified preinspection and permitted restarting of the balls when necessary. Material compositions and cleanliness of ball specimens are given in table I.

Race specimens were cylinders with an outside diameter of 4.750 inches and a length of 3.00 inches. Bore diameters ranged from 3.310 inches to 3.550 inches. Material compositions and cleanliness of cylinder specimens are given in table I.

All specimens were heat-treated according to standard bearing manufacturing practice to a hardness of Rockwell C-60 to C-63. All materials had cleanliness ratings (table I) of A-1 and D-1 or better on the ASTM Jernkontoret chart. For this reason, the materials were broken down further by dividing the cleanliness ratings arbitrarily into excellent to poor within this subgroup to give a more sensitive measure of relative cleanliness.

PROCEDURE

During storage, specimen surfaces were protected by a corrosion-resistant-oil film. Before test all race cylinders were given dimensional, surface-finish, and hardness inspections. All test balls were weighed and given a surface examination at a magnification of 36. A record was kept of any abnormalities in surface conditions at the running track. Prior to inspection and use, test specimens were flushed and scrubbed with absolute ethyl alcohol and clean cheesecloth. Care was taken during assembly not to scratch the running surfaces. The bore surface and test balls were coated with lubricant during assembly.

The rig was brought up to operating speed as rapidly and as smoothly as possible. Speed, air pressure, temperature, and vibration levels were recorded during the test. Total running time was recorded and converted into total stress cycles. A post-test surface examination at a magnification of 36 was made to observe track conditions. Failure data were plotted on Weibull paper, which is a distribution of the log log of the reciprocal of the portion of the sample surviving against the log of the

stress cycles to failure. From this plot the number of cycles necessary to fail any given portion of a sample group can be determined.

Groups of balls having different alloy compositions were run under rolling-contact fatigue conditions with an SAE 10 paraffinic-base mineral oil at room temperature. All tests were conducted at the loading which produced a maximum theoretical Hertz stress of 725,000 pounds per square inch in compression at the surface and 225,000 pounds per square inch in shear 0.009 inch below the surface unless otherwise stated. Results for tests at other stress levels were adjusted to the stress level of 725,000 pounds per square inch by the stress-life relation for the fatigue spin rig (Life = $K(1/\text{stress}^{10})$) determined in reference 5; race fatigue life data were produced under the same test conditions. A comparison is included of AISI M-1 vacuum- and air-melt heats which were run under the same test conditions, but the lubricant was a water-soluble polyalkylene glycol.

RESULTS

Weibull plots for the fatigue life obtained with the ball specimens are given in figure 2. A summary of these data is given in the following table:

Material	Cleanliness subgroup	10-Percent fatigue life	50-Percent fatigue life	Sample size	Number of failures	Number of runouts
SAE 52100	Poor	98×10^6	3200×10^6	74	27	47
AISI M-1	Fair	17.5×10^6	640×10^6	28	14	14
MHT	Poor	1080×10^6	3150×10^6	14	12	2
TMT	Poor	184×10^6	840×10^6	27	13	14
AISI M-10	Poor	290×10^6	1000×10^6	32	9	23
Halmo	Good	310×10^6	900×10^6	28	13	15
AISI T-1	Excellent	1150×10^6	4600×10^6	23	6	17
AISI MV-1	Good	508×10^6	4200×10^6	30	22	8
AISI M-50	Good	550×10^6	6800×10^6	29	13	16
AISI M-1[a]	Fair	7.6×10^6	152×10^6	16	11	5
AISI M-1[a] (vacuum-melt)	Excellent	85×10^6	1150×10^6	13	11	2

[a]Run with glycol lubricant.

Weibull plots for the fatigue life obtained with the race specimens are given in figure 3. The life results for races cannot be compared directly with life results for balls because of the different stress

volumes involved. Since the track length of the races is approximately seven times that of the balls, one race track has a stressed volume equivalent to seven times that of a ball track. Thus, one race failure is equivalent to one failed ball and six unfailed balls (i.e., a race failure is the minimum life value for a volume of material seven times that of a ball), and the probability of attaining a given survival level (i.e., percent of sample unfailed) is equivalent to the probability of the same survival level in the ball raised to the seventh power. Thus, a 90-percent survival level in a 1/2-inch ball is equivalent to a 47.8-percent survival level in a 3.5-inch-diameter race. With this relation, the equivalent life for races at the same stressed volume as a 1/2-inch ball can be determined and is shown in figure 3. Since the stress level is higher than the standard 725,000 pounds per square inch at which the balls were run, a further adjustment for stress must be made according to the relation of reference 5 (Life = $K(1/\text{stress}^{10})$). The result is a life relation which is equivalent to that of a 1/2-inch ball run at the standard test conditions, and a comparison can be made between ball and race data. These adjusted Weibull plots are also given in figure 3. A summary of these data is given in the following table:

Material	10-Percent life		50-Percent life		Sample size	Number of failures	Number of run-outs
	Actual	Adjusted	Actual	Adjusted			
AISI M-1	7.6×10^6	82×10^6	56×10^6	570×10^6	29	23	6
AISI M-1 (vacuum-melt)	28×10^6	930×10^6	560×10^6	$17,000\times10^6$	19	12	7
MV-1	10.3×10^6	130×10^6	86×10^6	$1,100\times10^6$	40	31	9
AISI T-1	4.7×10^6	42×10^6	27.5×10^6	260×10^6	50	50	0

CONCLUDING REMARKS

In order to facilitate comparison of the life data in figure 2, a summary of 10- and 50-percent failure lives for the ball groups is made in bar graph form in figure 4. The race data are presented in figure 5 both in the original form and adjusted for stressed volume and stress to give results equivalent to those for the 1/2-inch balls.

For reasons of statistical reliability and of material nonhomogeneity it is felt that no conclusions regarding the fatigue life of an alloy designation can be made without testing many heats of the alloy. The data presented under this cover are therefore considered preliminary.

Beneficial effects were observed with vacuum-melting. A group of vacuum-melted AISI M-1 balls showed a significant increase in life over a group of air-melted AISI M-1 balls run at the same test conditions (figs. 4(k) and (j)). The improvement was of the order of magnitude of 10 to 1. The vacuum-melted balls were rated excellent in cleanliness, while the air-melted balls were rated as fair. A similar increase in fatigue life was observed with the AISI M-1 race specimens (figs. 5(a) and (b)). No attempt was made to compare the cleanliness within the A-1 and D-1 classifications of these two groups of races.

The SAE 52100 base alloys which were modified by further aluminum and silicon additions, with or without molybdenum modifications, showed improvement over standard SAE 52100 (fig. 4(a)). MHT (fig. 4(c)) had about 1 percent aluminum added, and TMT (fig. 4(d)) had 1 percent silicon content. With these materials, fewer short-lived failures were obtained, and the scatter in life (as measured by the difference between the 10- and 50-percent lives) was reduced. All three groups of specimens, which were of the same cleanliness, were rated as poor within the ASTM A-1 and D-1 classifications.

No correlation of fatigue life with cleanliness was obtained for the various specimens. The effect of the different alloy compositions may have been large enough to obscure any definite correlation, if it did exist.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, November 13, 1957

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2. Barnes, Gilbert C., and Ryder, Earle A.: A Look at Some Turbine Bearing Problems. Preprint No. 693, SAE, 1956.

3. Macks, E. F.: Fatigue Spin Rig - A New Apparatus for Rapidly Evaluating Materials and Lubricants for Rolling Contact. Lubrication Eng., vol. 9, no. 5, Oct. 1953, pp. 254-258.

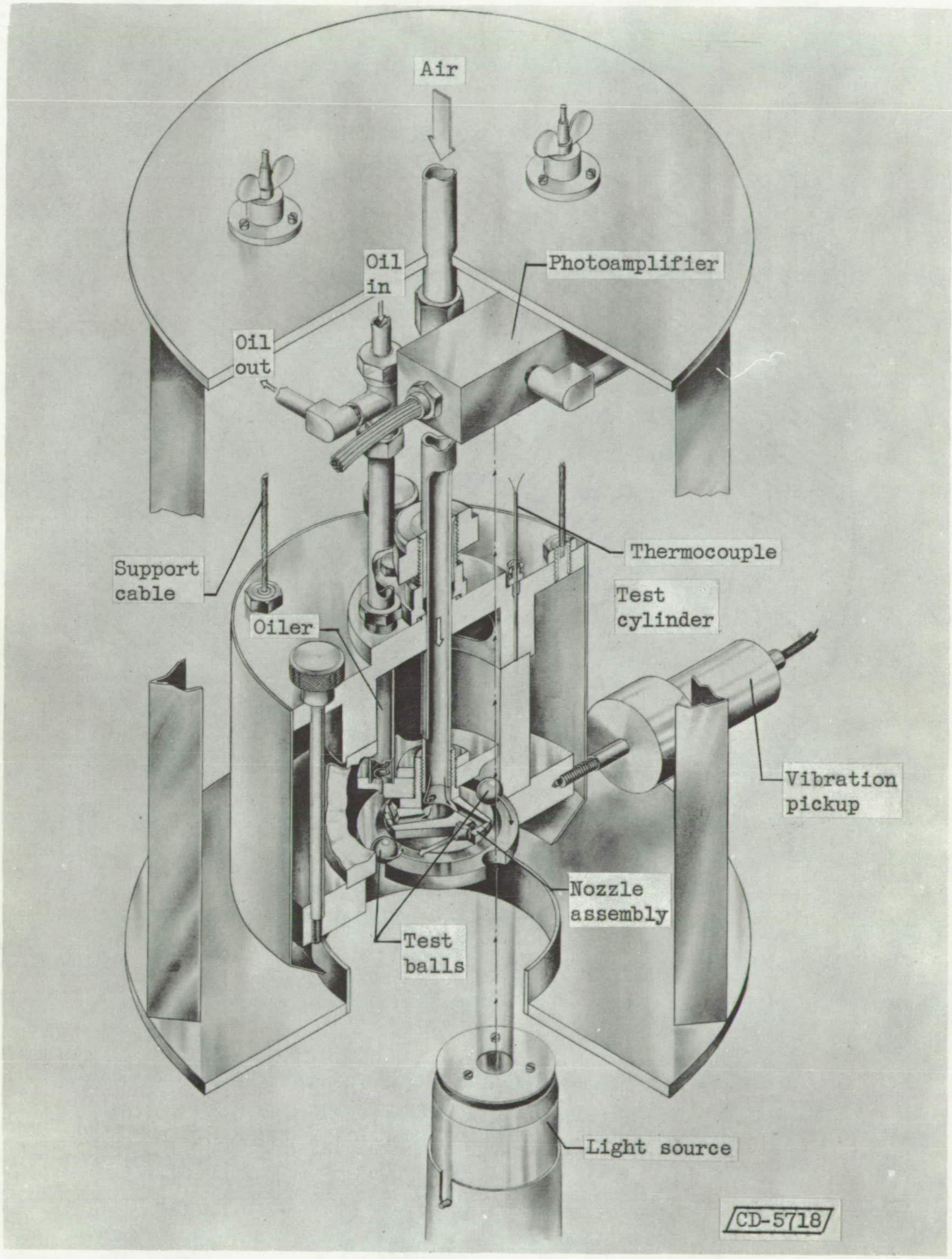
4. Jones, A. B.: New Departure - Analysis of Stresses and Deflections. Vol. I and II. New Departure, Div. General Motors Corp., Bristol (Conn.), 1946.

5. Butler, Robert H., and Carter, Thomas L.: Stress-Life Relations of the Rolling-Contact Fatigue Spin Rig. NACA TN 3930, 1957.

6. Carter, Thomas L.: Effect of Lubricant Base Stock on Rolling-Contact Fatigue Life. NACA TN 4161, 1957.

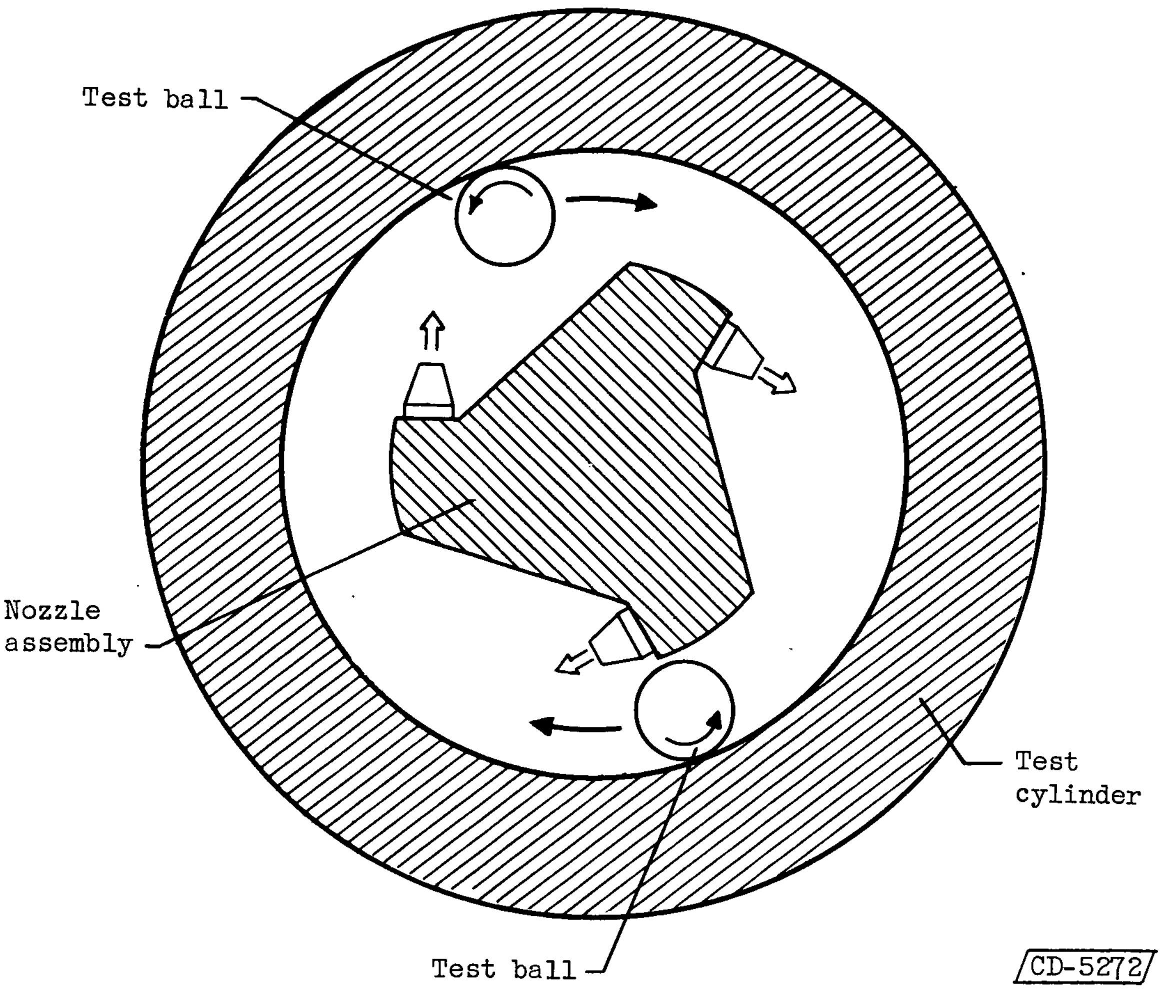
TABLE 1. - ANALYSIS AND CLEANLINESS OF BALL AND CYLINDER SPECIMENS

Specimens	ASTM cleanliness		Cleanliness subgroup	Analysis (specified)									
	A-	D-		C	P	S	Mn	Si	Al	Cr	V	W	Mo
Balls:													
SAE 52100 (air-melt)	1	1	Poor	1.00	0.025 Max.	0.025 Max.	0.35	0.28	----	1.45	----	-----	----
AISI M-1 (air-melt)	1	1	Fair	0.80	0.030 Max.	0.030 Max.	0.23	0.23	----	4.00	1.00	1.50	8.00
MHT (air-melt)	1	1	Poor	0.98	0.025 Max.	0.025 Max.	0.40	0.54	1.25	1.38	----	-----	----
TMT (air-melt)	1	1	Poor	1.00	0.025 Max.	0.025 Max.	0.50	1.00	0.08	1.45	----	-----	0.30
AISI M-10 (air-melt)	1	1	Poor	0.85	0.030 Max.	0.030 Max.	0.23	0.30	----	4.00	2.00	-----	8.00
Halmo (vacuum-melt)	1	1	Good	0.65	0.030 Max.	0.030 Max.	0.27	1.2	----	4.72	0.55	-----	5.36
AISI T-1 (air-melt)	1	1	Excellent	0.70	0.030 Max.	0.030 Max.	0.30	0.25	----	4.00	1.00	18.00	----
AISI MV-1 (air-melt)	1	1	Good	0.80	0.030 Max.	0.030 Max.	0.30	0.25	----	4.10	1.10	-----	4.25
AISI M-50 (air-melt)	1	1	Good	0.80	0.030 Max.	0.030 Max.	0.30	0.25	----	4.00	1.10	-----	4.00
AISI M-1 (vacuum-melt)	1	1	Excellent	0.80	0.030 Max.	0.030 Max.	0.23	0.23	----	4.00	1.00	1.50	8.00
Cylinders:													
AISI M-1 (air-melt)	1	1	------	0.80	0.030 Max.	0.030 Max.	0.23	0.23	----	4.00	1.00	1.50	8.00
AISI M-1 (vacuum-melt)	1	1	------	0.80	0.030 Max.	0.030 Max.	0.23	0.23	----	4.00	1.00	1.50	8.00
AISI MV-1 (air-melt)	1	1	------	0.80	0.030 Max.	0.030 Max.	0.30	0.25	----	4.10	1.10	-----	4.25
AISI T-1 (air-melt)	1	1	Fair	0.70	0.030 Max.	0.030 Max.	0.30	0.25	----	4.00	1.00	18.00	----



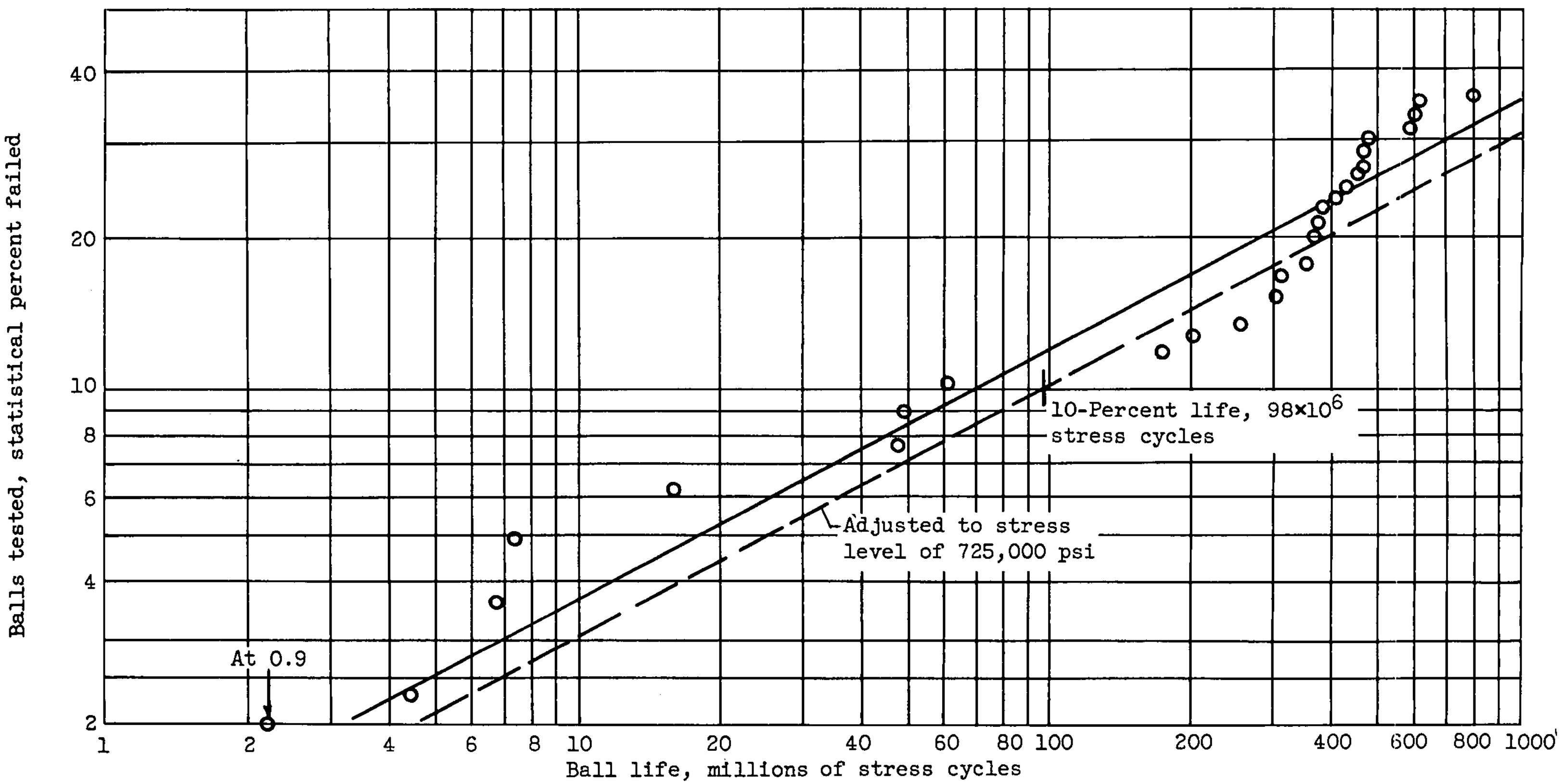
(a) Cutaway view.

Figure 1. - Rolling-contact fatigue spin rig.



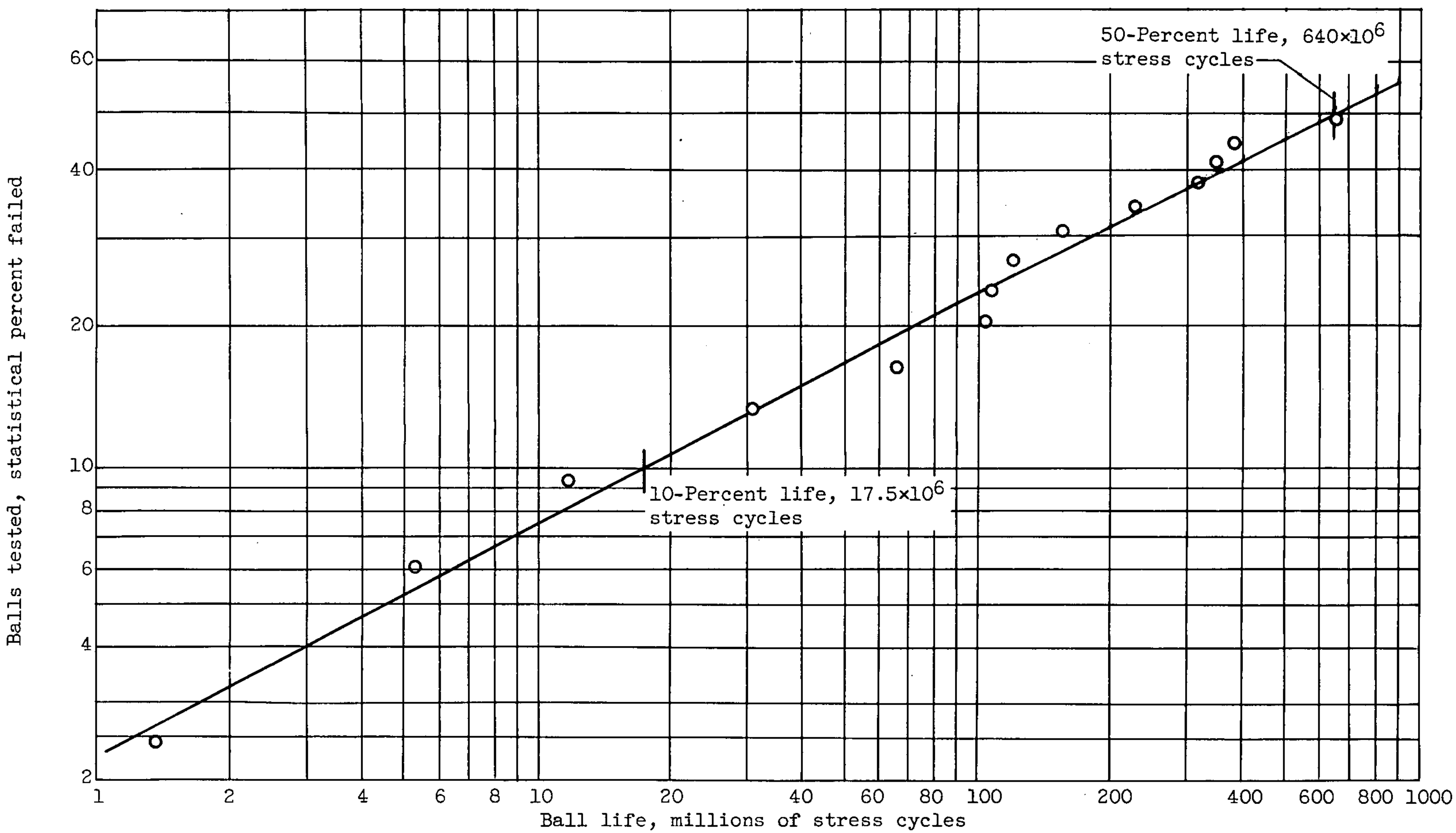
(b) Schematic diagram of test cylinder.

Figure 1. - Concluded. Rolling-contact fatigue spin rig.



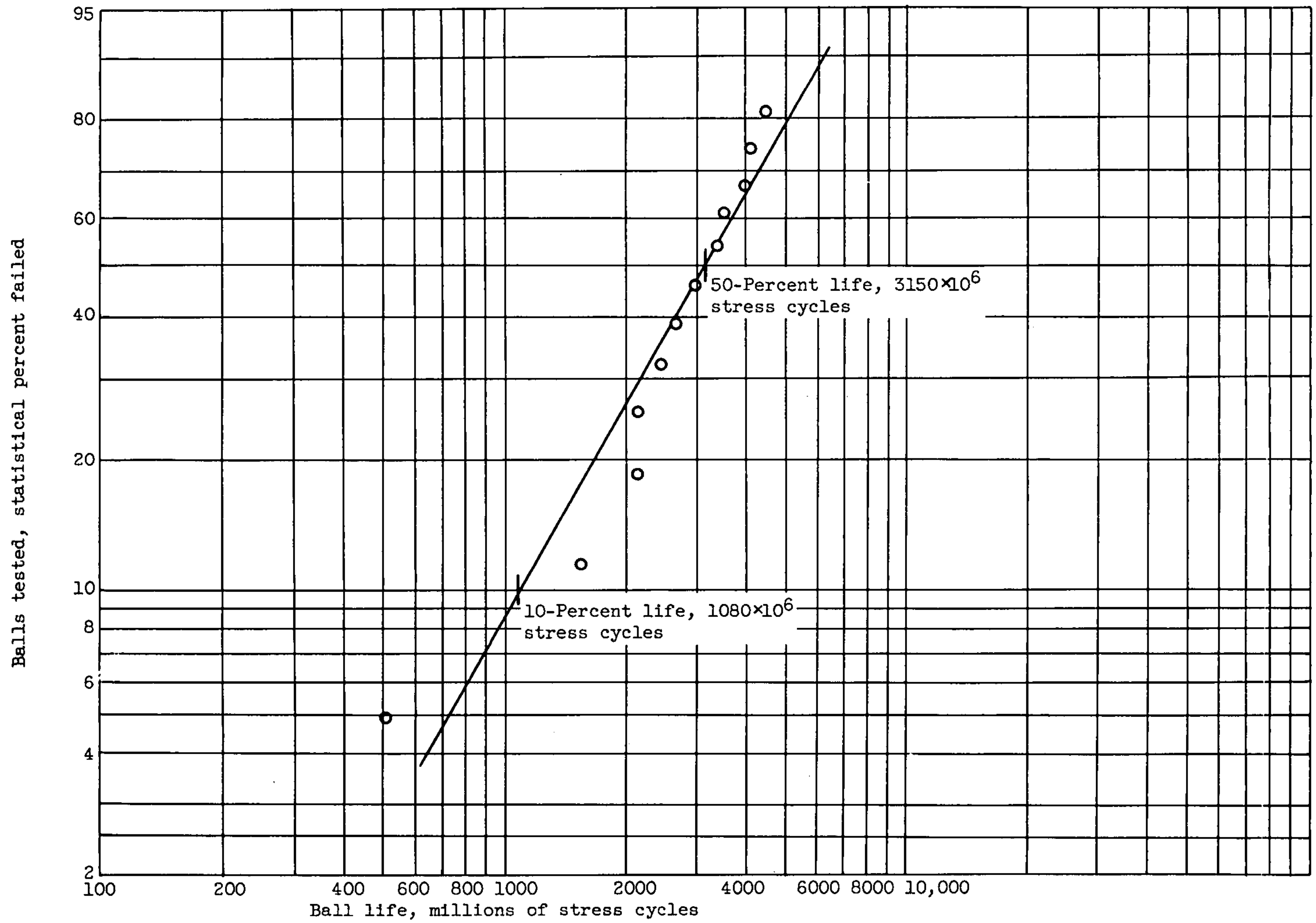
(a) Air-melt SAE 52100; room temperature; lubricant, SAE 10 mineral oil; maximum Hertz compressive stress, 750,000 pounds per square inch; sample size, 74.

Figure 2. - Fatigue life of ball materials.



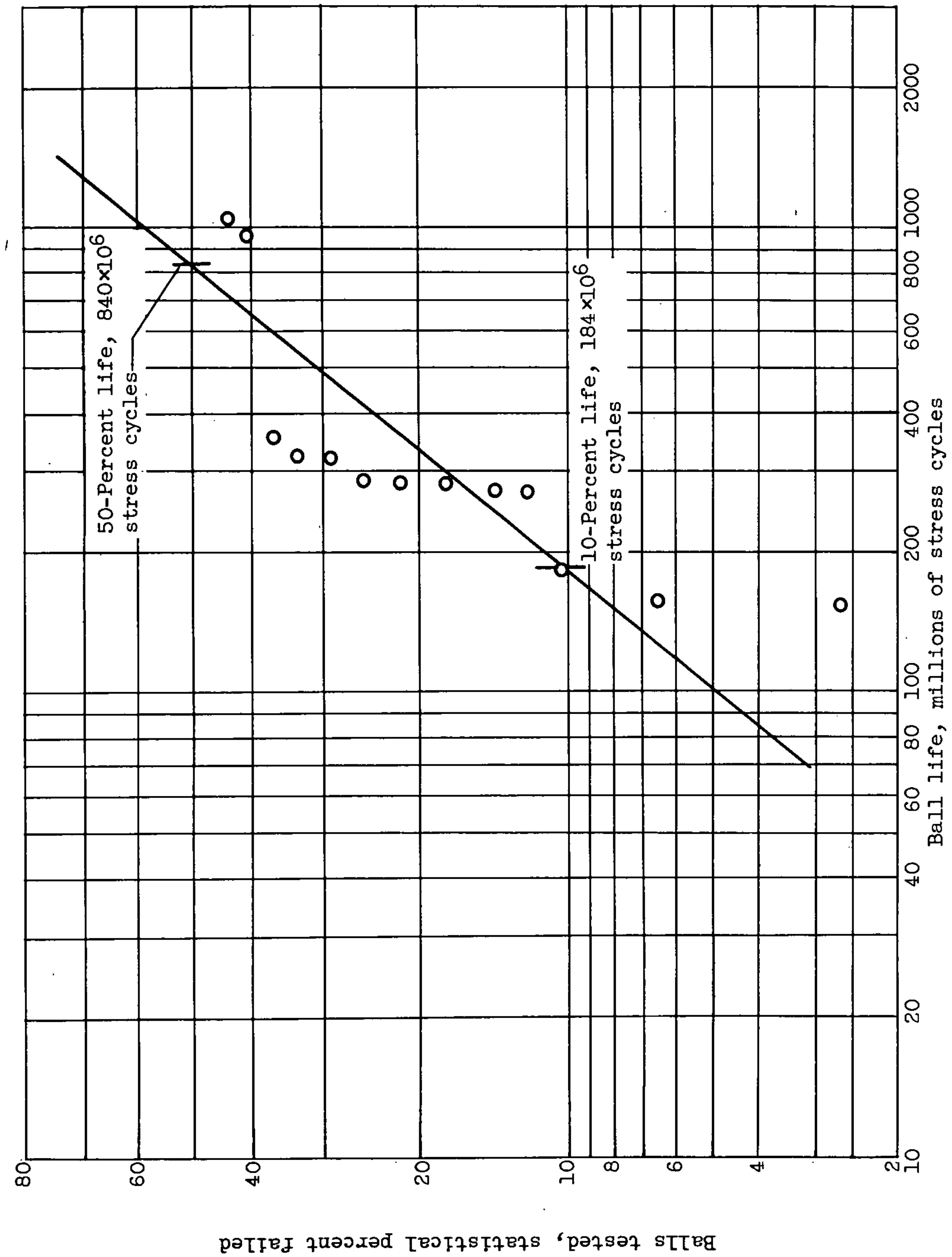
(b) Air-melt AISI M-1; room temperature; lubricant, SAE 10 mineral oil; maximum Hertz compressive stress, 725,000 pounds per square inch; sample size, 28.

Figure 2. - Continued. Fatigue life of ball materials.



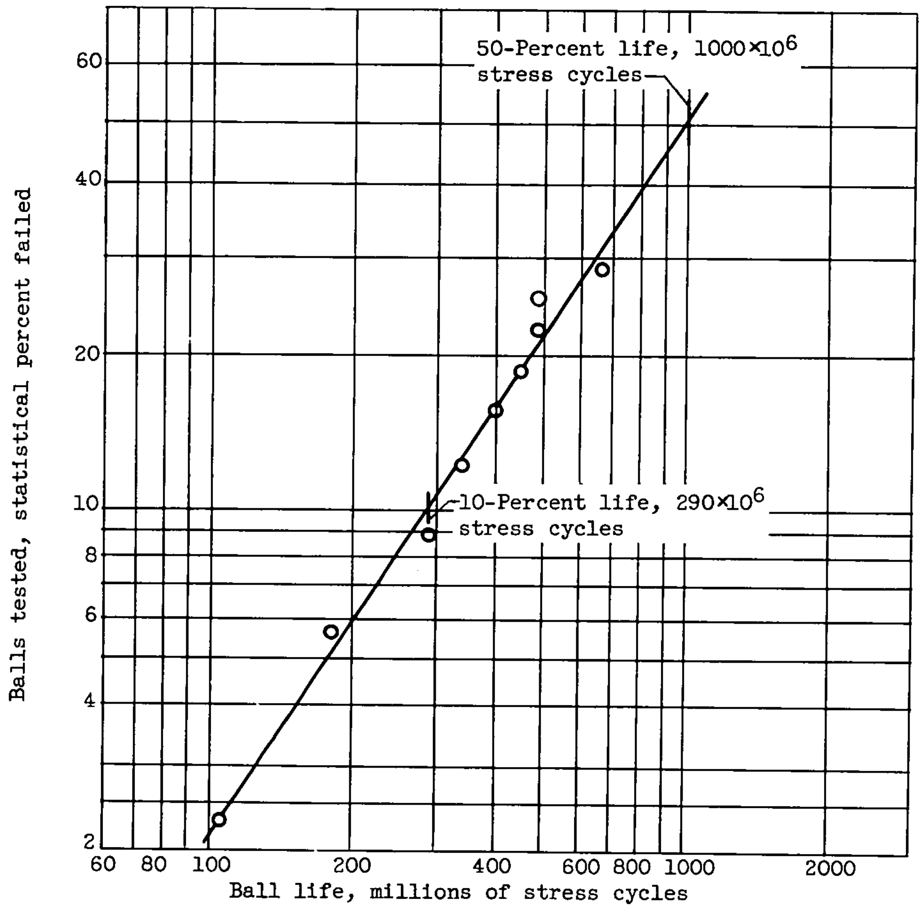
(c) Air-melt MHT; room temperature; lubricant, SAE 10 mineral oil; maximum Hertz compressive stress, 725,000 pounds per square inch; sample size, 14.

Figure 2. - Continued. Fatigue life of ball materials.



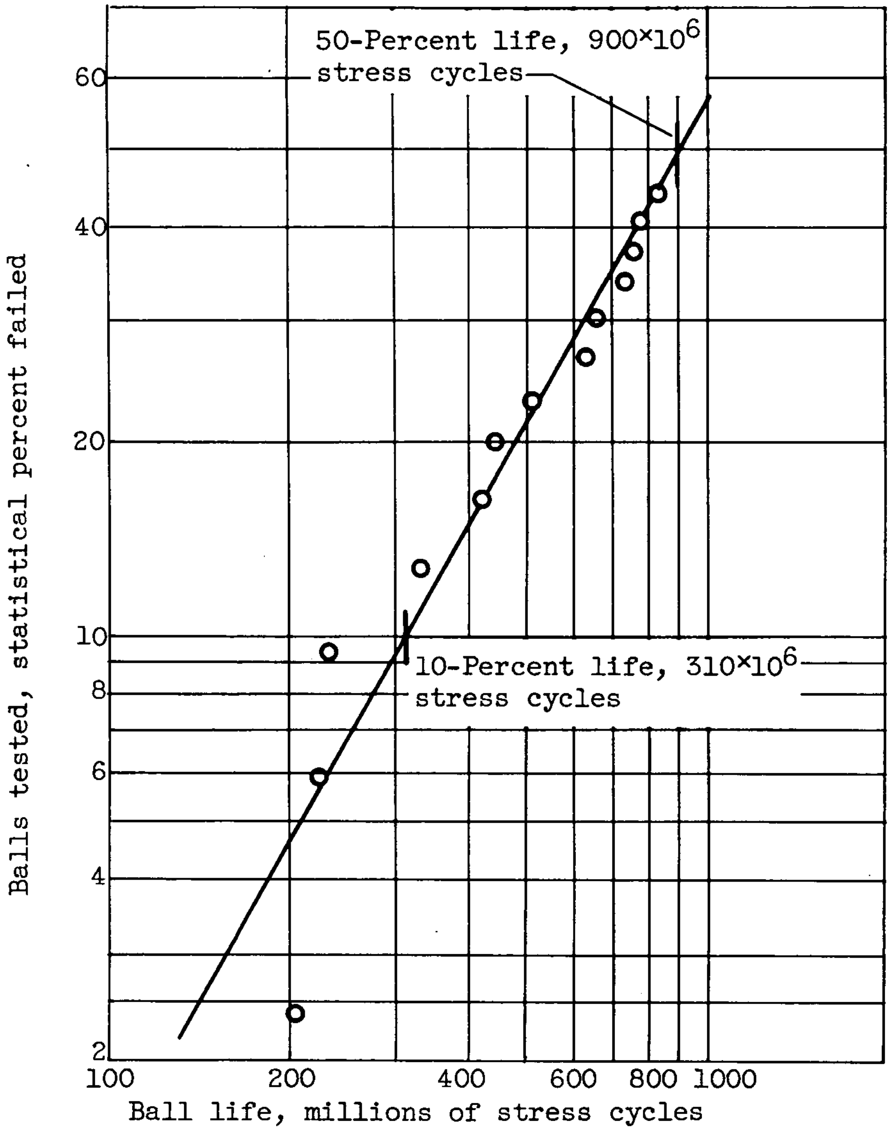
(d) Air-melt TMT; room temperature; lubricant, SAE 10 mineral oil; maximum Hertz compressive stress, 725,000 pounds per square inch; sample size, 27.

Figure 2. - Continued. Fatigue life of ball materials.



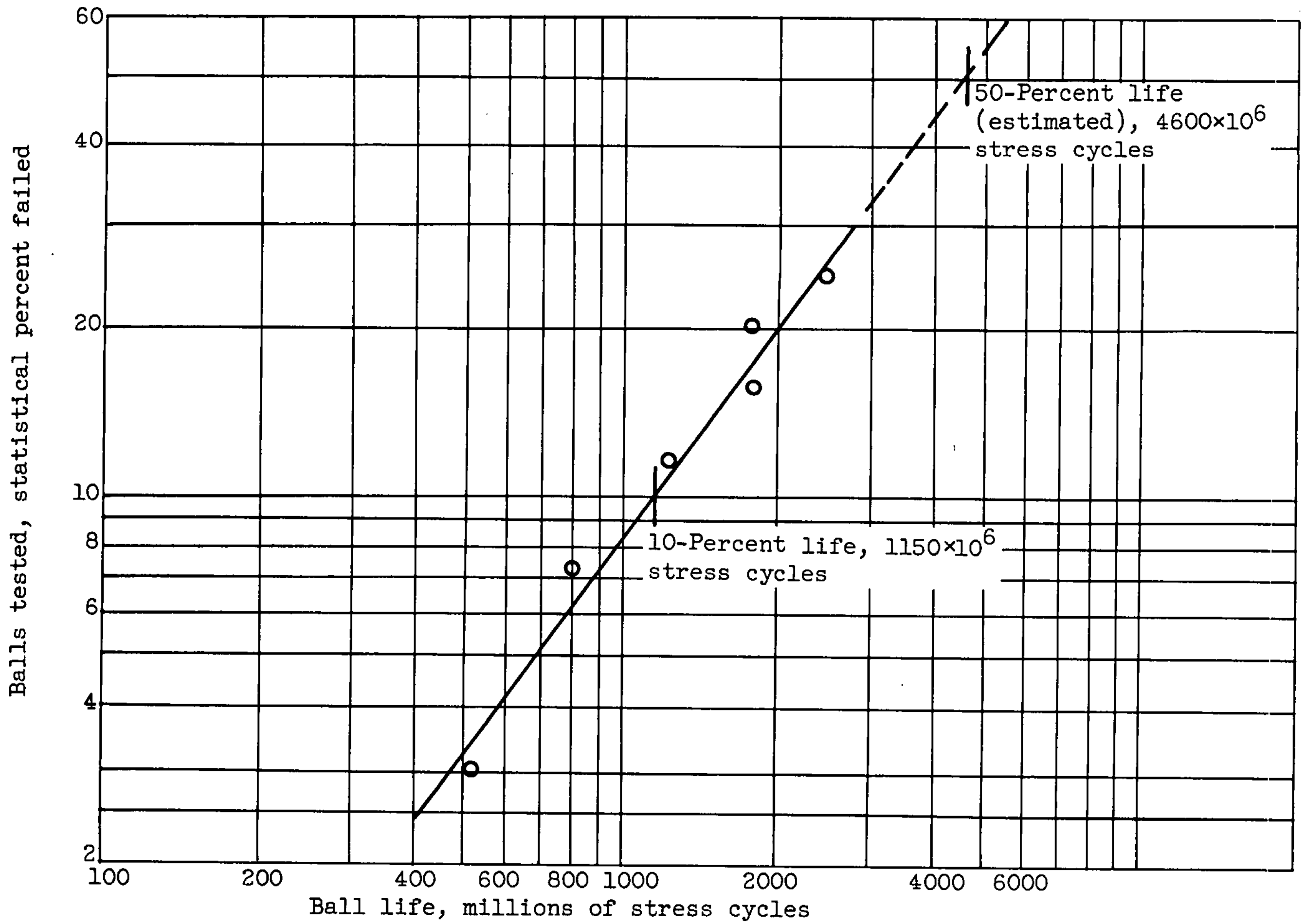
(e) Air-melt AISI M-10; room temperature; lubricant, SAE 10 mineral oil; maximum Hertz compressive stress, 725,000 pounds per square inch; sample size, 32.

Figure 2. - Continued. Fatigue life of ball materials.



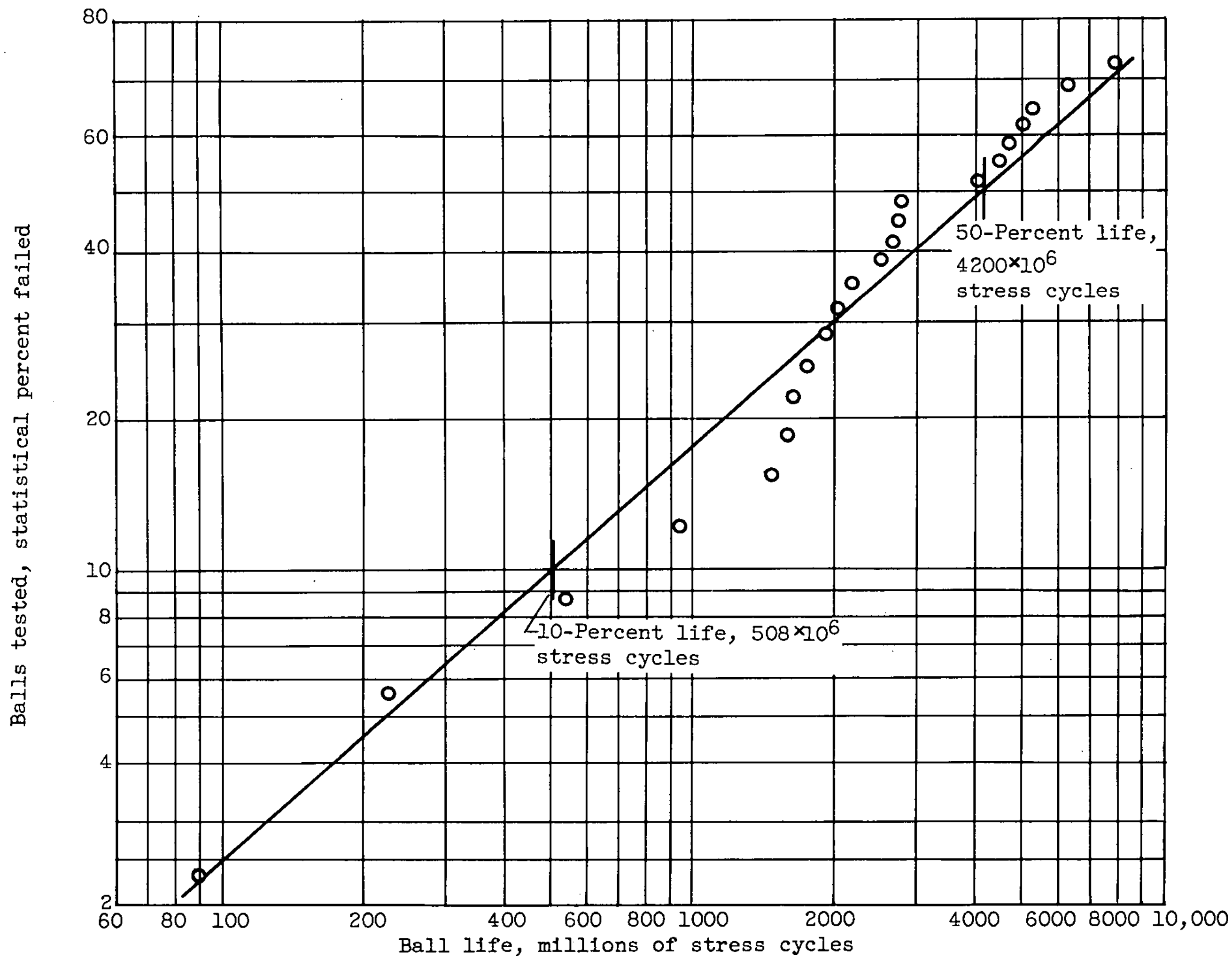
(f) Vacuum-melt Halmo; room temperature; lubricant, SAE 10 mineral oil; maximum Hertz compressive stress, 725,000 pounds per square inch; sample size, 28.

Figure 2. - Continued. Fatigue life of ball materials.



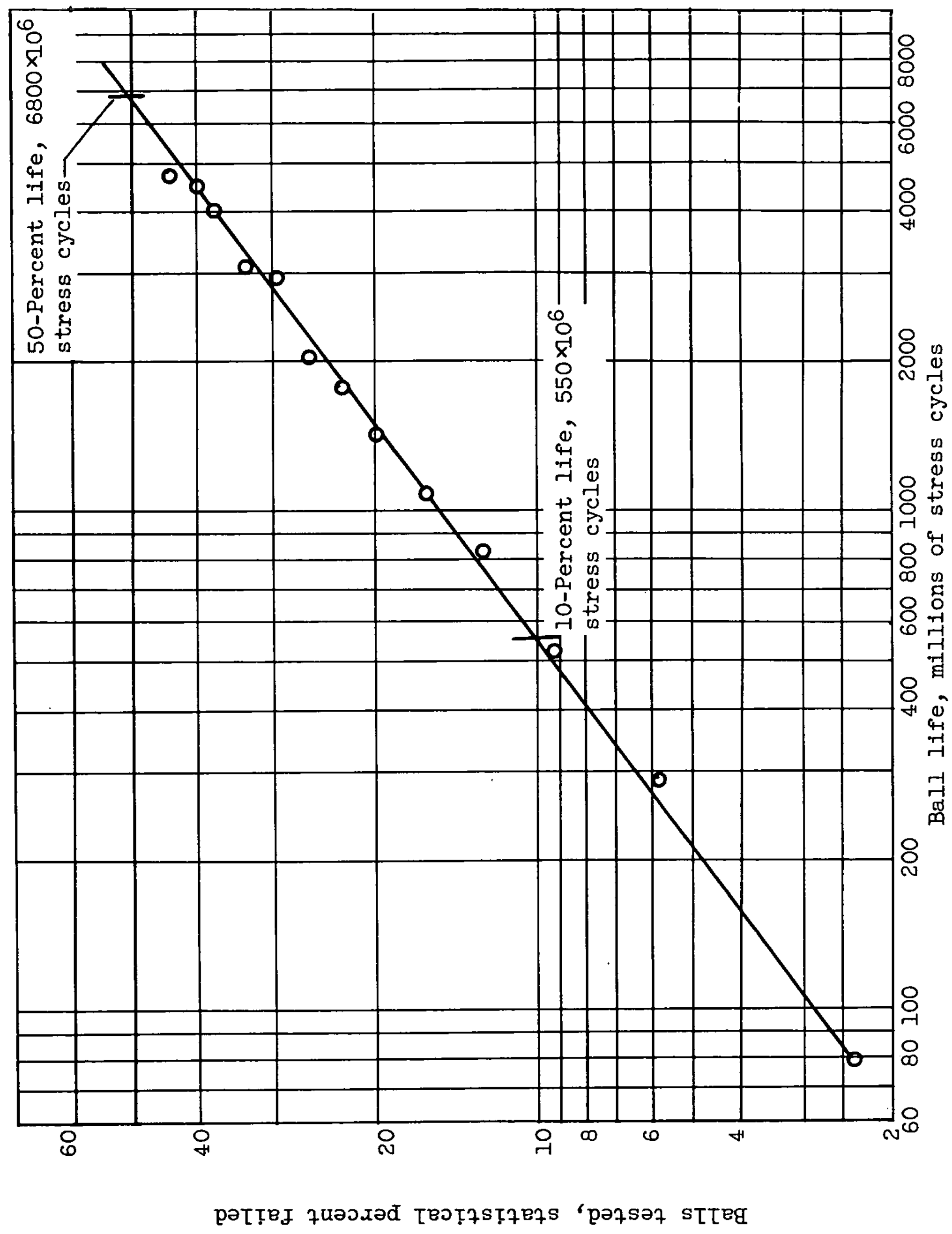
(g) Air-melt AISI T-1; room temperature; lubricant, SAE 10 mineral oil; maximum Hertz compressive stress, 725,000 pounds per square inch; sample size, 23.

Figure 2. - Continued. Fatigue life of ball materials.



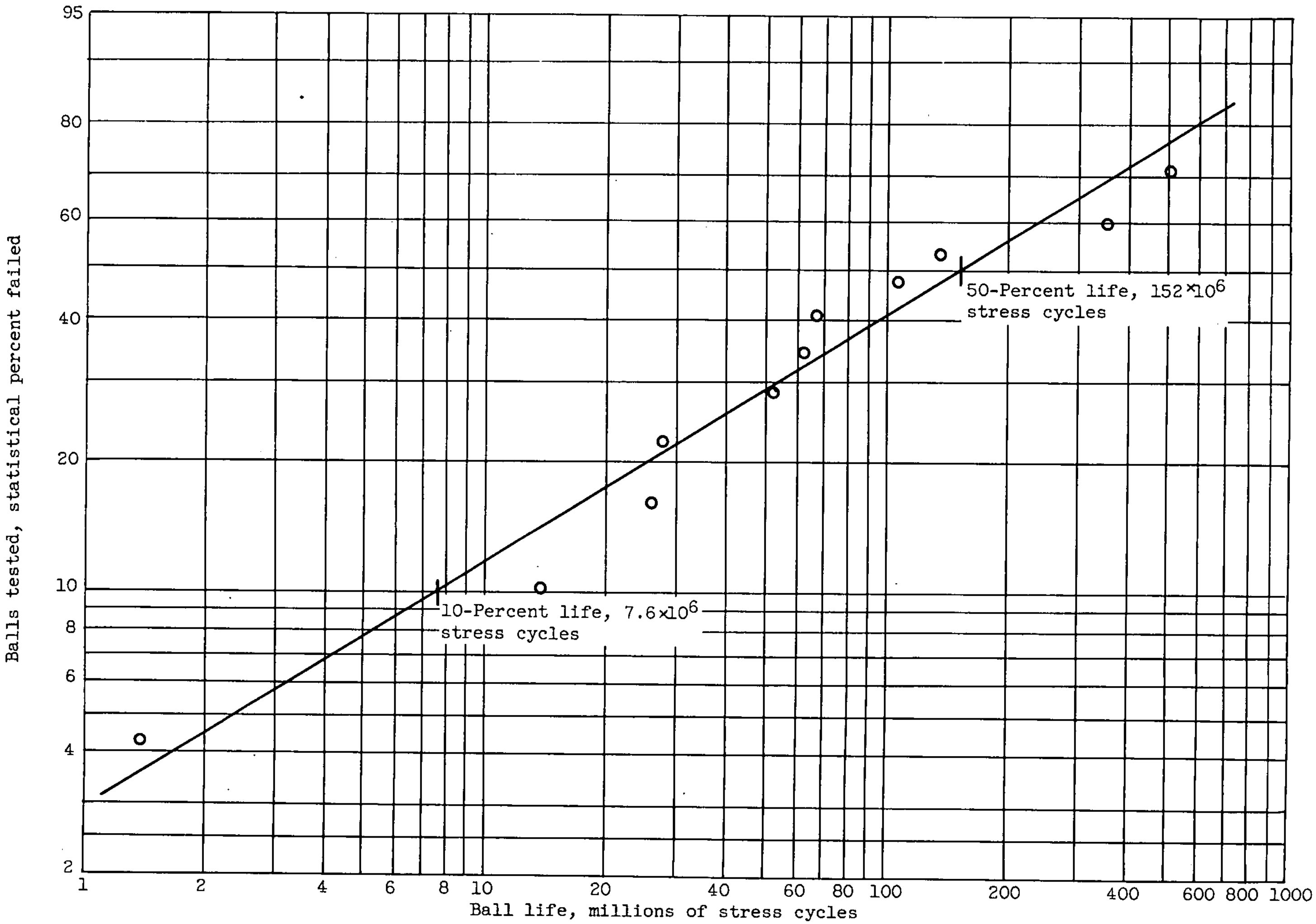
(h) Air-melt MV-1; room temperature; lubricant, SAE 10 mineral oil; maximum Hertz compressive stress, 725,000 pounds per square inch; sample size, 30.

Figure 2. - Continued. Fatigue life of ball materials.



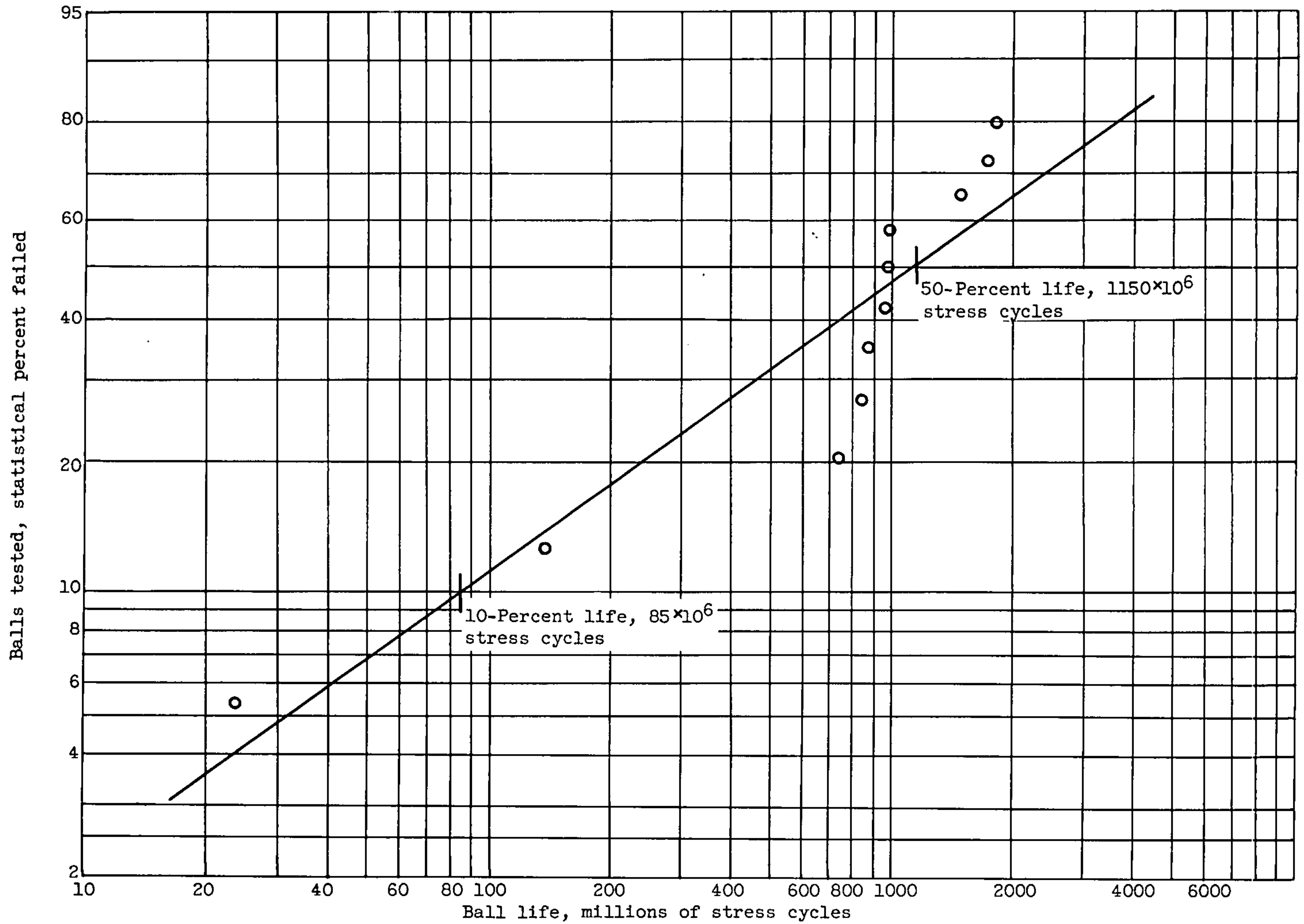
(i) AISI M-50; room temperature; lubricant, SAE 10 mineral oil; maximum Hertz compressive stress, 725,000 pounds per square inch; sample size, 29.

Figure 2. - Continued. Fatigue life of ball materials.



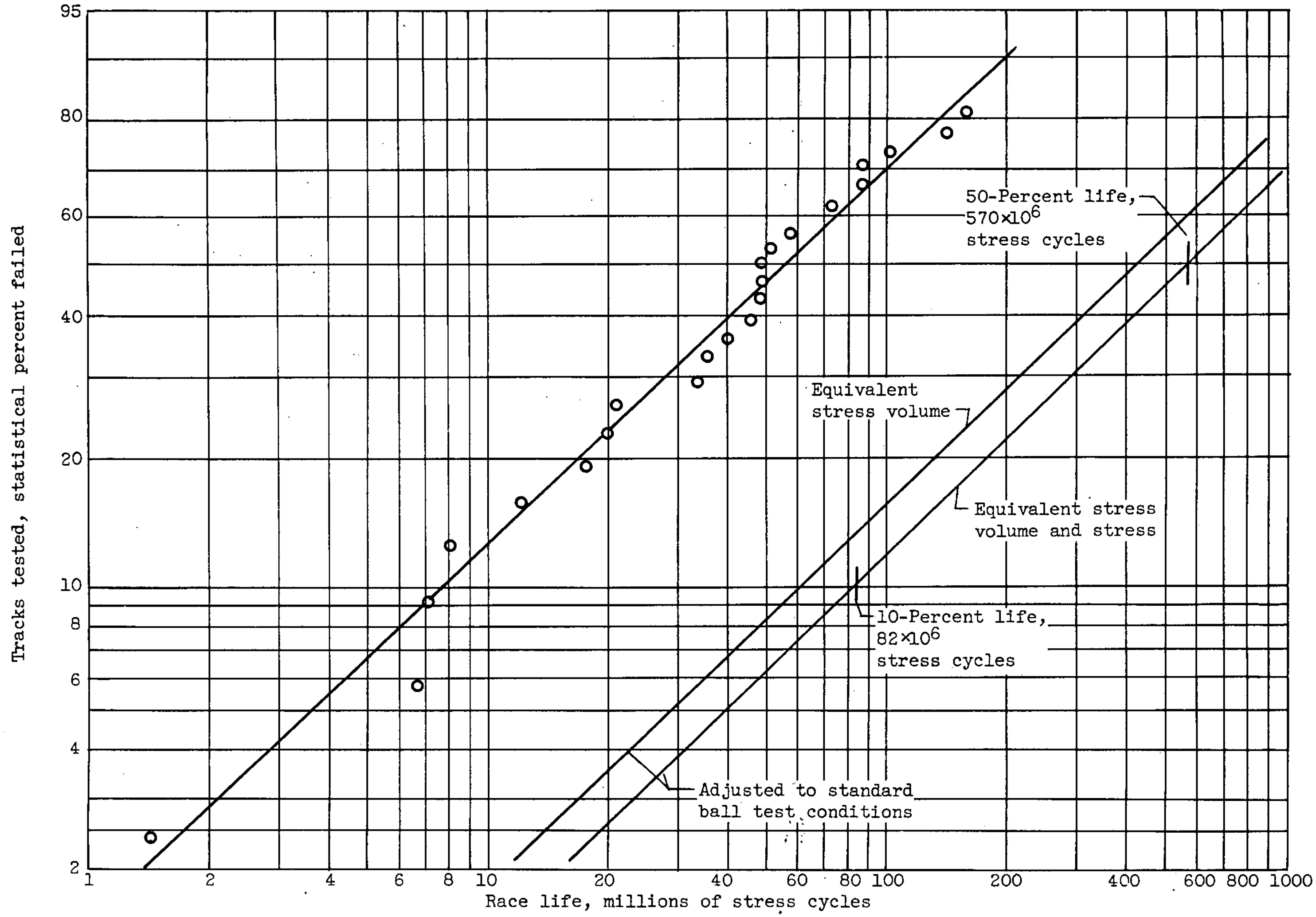
(j) Air-melt AISI M-1; temperature, 100° F; lubricant, polyalkylene glycol; maximum Hertz compressive stress, 725,000 pounds per square inch; sample size, 16.

Figure 2. - Continued. Fatigue life of ball materials.



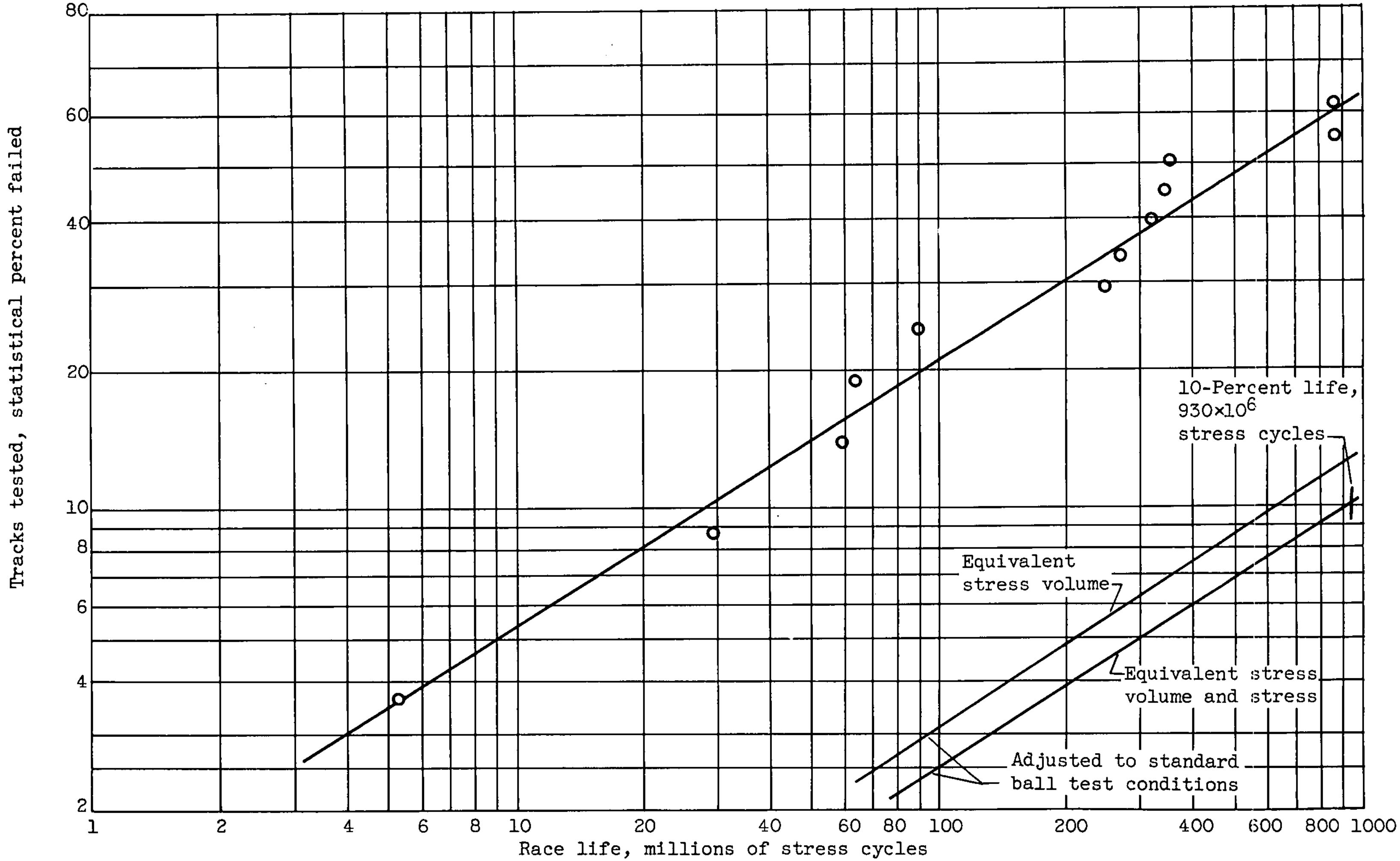
(k) Vacuum-melt AISI M-1; temperature, 100° F; lubricant, polyalkylene glycol; maximum Hertz compressive stress, 725,000 pounds per square inch; sample size, 13.

Figure 2. - Concluded. Fatigue life of ball materials.



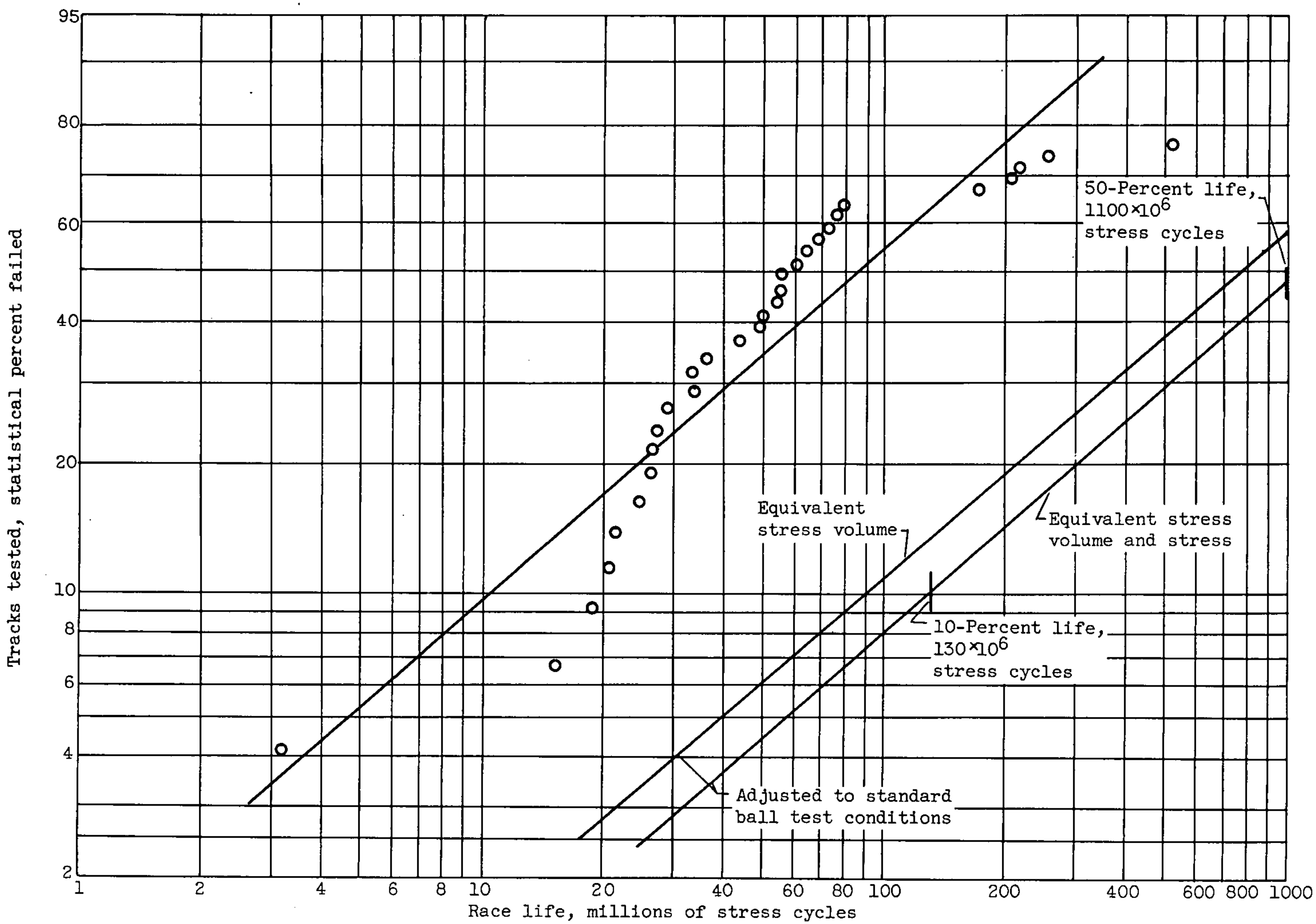
(a) Air-melt AISI M-1; sample size, 29.

Figure 3. - Fatigue life of race materials. Room temperature; lubricant, SAE 10 mineral oil; maximum Hertz compressive stress, 750,000 pounds per square inch.



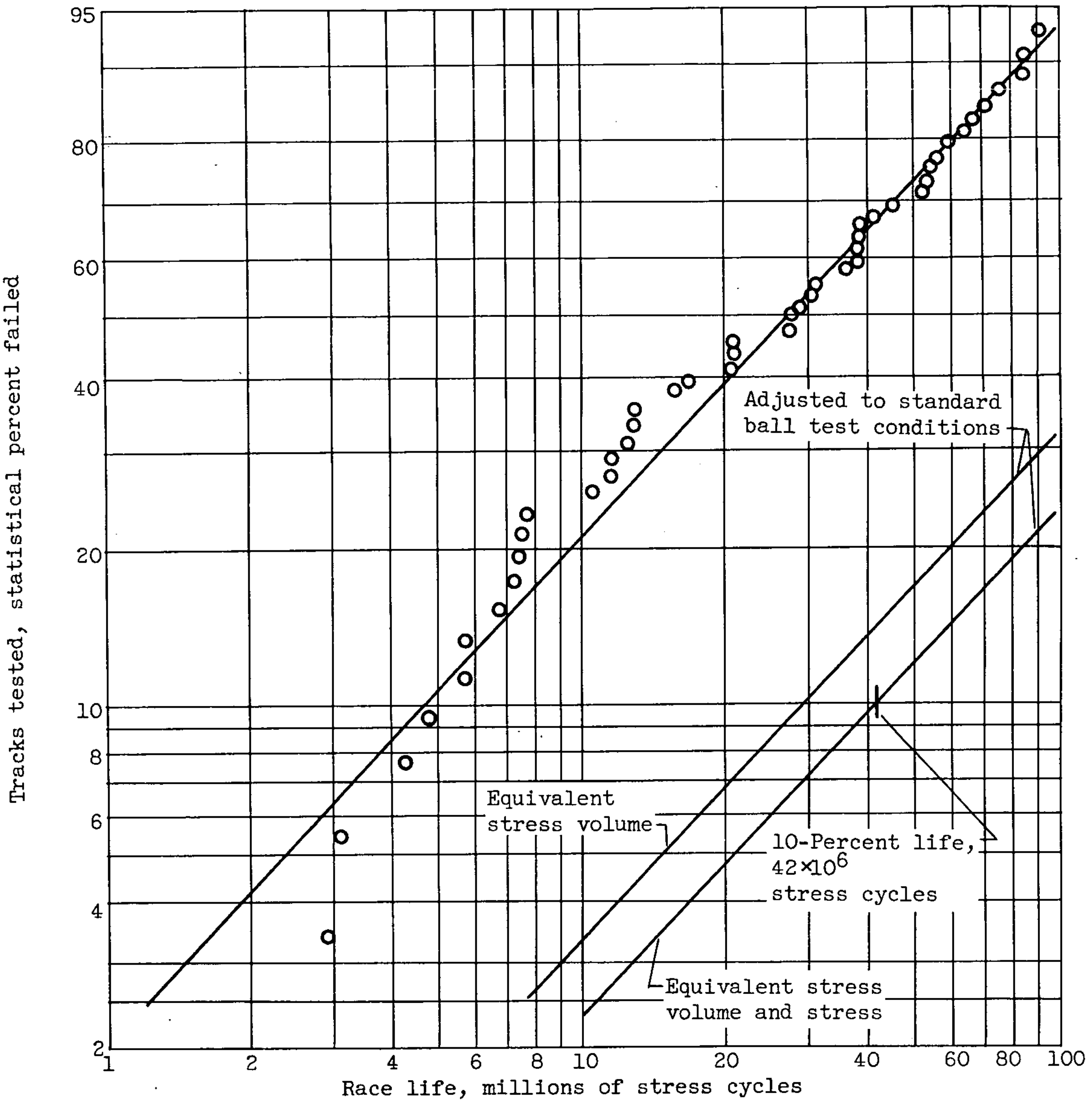
(b) Vacuum-melt AISI M-1; sample size, 19.

Figure 3. - Continued. Fatigue life of race materials. Room temperature; lubricant, SAE 10 mineral oil; maximum Hertz compressive stress, 750,000 pounds per square inch.



(c) Air-melt MV-1; sample size, 40.

Figure 3. - Continued. Fatigue life of race materials. Room temperature; lubricant, SAE 10 mineral oil; maximum Hertz compressive stress, 750,000 pounds per square inch.



(d) Air-melt AISI T-1; sample size, 50.

Figure 3. - Concluded. Fatigue life of race materials. Room temperature; lubricant, SAE 10 mineral oil; maximum Hertz compressive stress, 750,000 pounds per square inch.

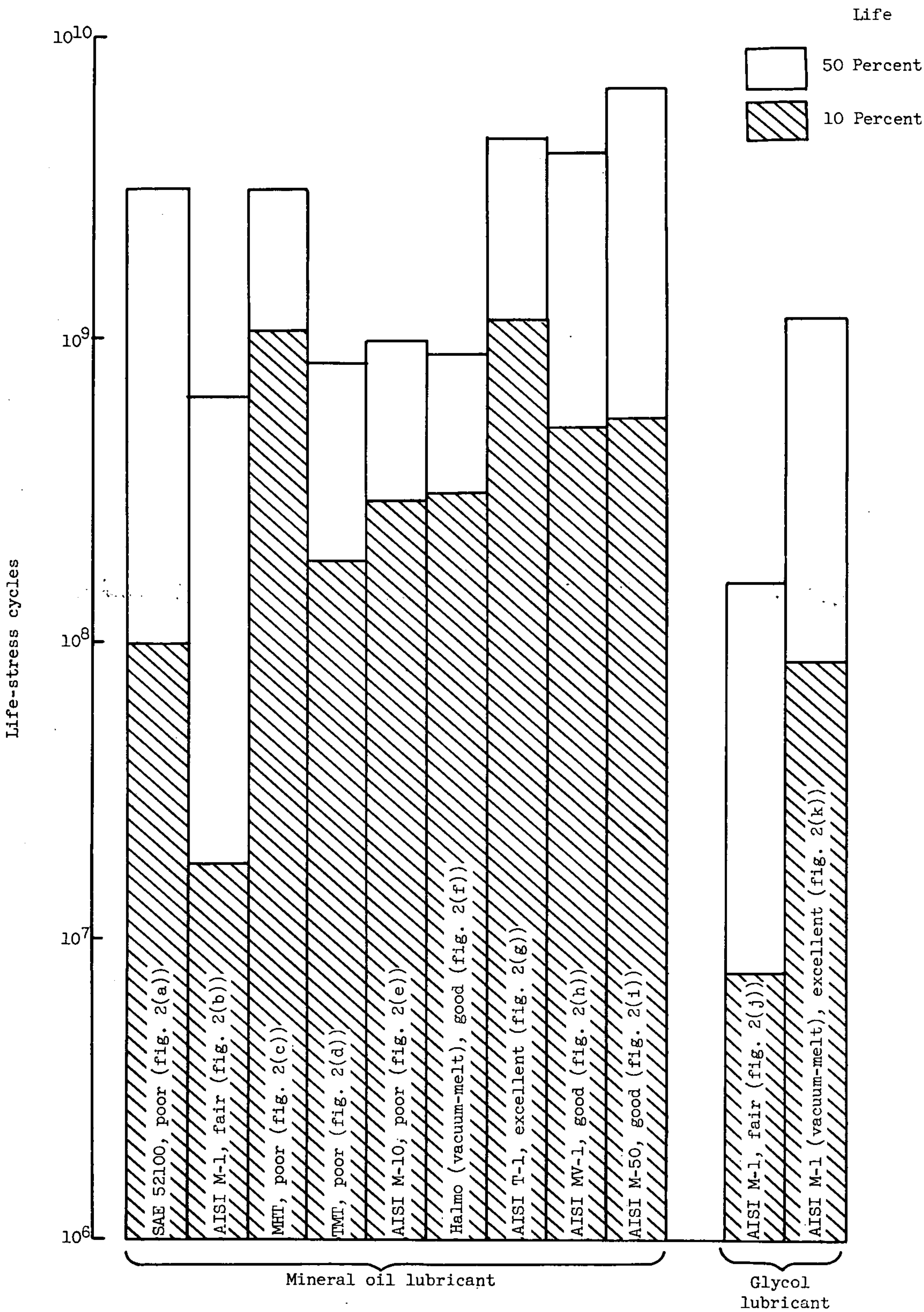


Figure 4. - Summary of ball life data giving material, cleanliness ranking, and figure number.

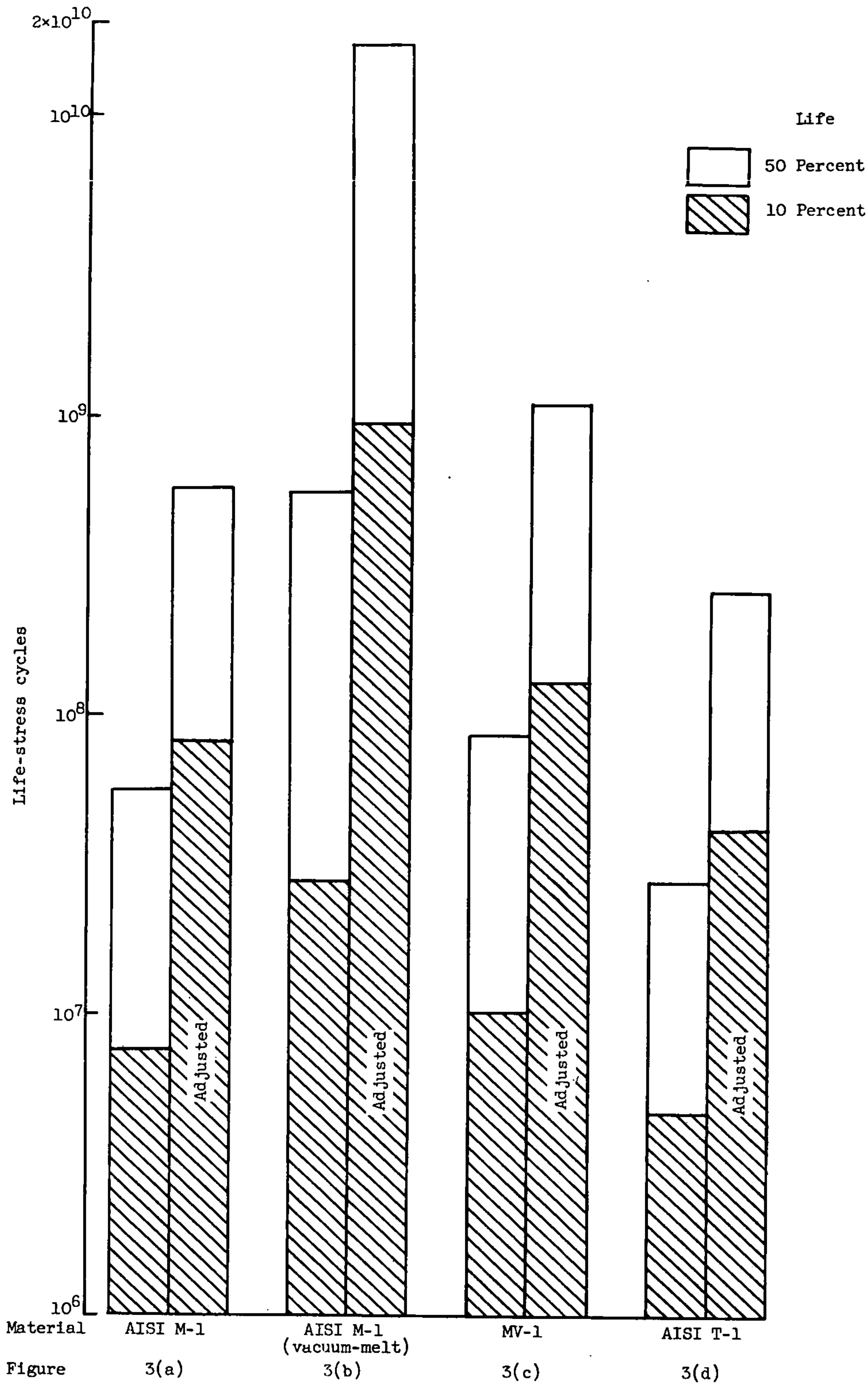


Figure 5. - Summary of race life data as compiled and adjusted to equivalent stress volume and stress of 1/2-inch balls. Lubricant, SAE 10 mineral oil.

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